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A viable one-family technicolor model

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Abstract

We construct a one-family technicolor model which is consistent with the precision experiments on the electroweak interaction. The Majorana mass of the right-handed techni-neutrino is introduced and the techni-$U(1)_{B-L}$ symmetry is gauged to obtain the correct breaking of the electroweak symmetry. The tree-level kinetic mixing between the techni-$U(1)_{B-L}$ and $U(1)_Y$ gauge bosons plays an important role for having the consistent value of the S parameter.

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The recent experiments on the electroweak interaction give strong constraints on the technicolor theory. Especially, the data on the oblique correction, which is parameterized by three parameters S, T, and U [1], directly constrain the scenario of the dynamical electroweak symmetry breaking by the technicolor interaction. The naive QCD-like one-family technicolor model has been already excluded, since it generally gives large values of $S \geq 0.8$ for $N_{TC} \geq 2$. These values are about 3.5-σ or more away from the value favored by the experiments with a reference point $m_t = 175\text{GeV}$ and $m_H = 1\text{TeV}$ [2]. The QCD-like one-doublet model gives smaller values of $S \geq 0.2$ for $N_{TC} \geq 2$, which are, however, about 1-σ or more away from the value favored by the experiments. Therefore, many mechanisms to generate the small value of S have been considered in the technicolor theory. The walking technicolor dynamics itself [3,4], the additional $U(1)$ gauge boson which mixes with the electroweak gauge bosons [5], unusual mass spectrum of the techni-fermions [6,7], and exotic quantum numbers of the techni-fermions in the electroweak gauge interaction [8], have been proposed so far to yield a technicolor model with the small S parameter.

In this letter we consider the technicolor model where the right-handed techni-neutrino has a Majorana mass [6] which is the remaining degree of freedom of the one-family technicolor model. Both the left-handed and right-handed techni-neutrino must belong to the real representation of the technicolor gauge group to have the gauge-invariant Majorana mass, while keeping the technicolor interaction vector-like. Since the smallness of the S parameter suggests the small technicolor sector (small number of the weak doublets), we consider the smallest system. We assign the techni-leptons to the adjoint representations of $SU(2)^L_{TC}$ (or the fundamental representations of $SO(3)^L_{TC}$), and assign the techni-quarks to the fundamental representations of $SU(3)^Q_{TC}$.

Since the techni-leptons are in the real representations of the strong $SU(2)^L_{TC}$, there is no distinction between the Dirac condensate $\langle \bar{N}_R N_L \rangle$ and the Majorana condensate $\langle N_L N_L \rangle$, where N denotes the techni-neutrino. The Majorana condensate of the left-handed techni-neutrino is more favorable than the Dirac condensate, because of the presence of the Majo-

rana mass of N_R [1]. There must be some interactions which can assist the Dirac condensate. We gauge the techni-$U(1)_{B-L}$ symmetry, $U(1)^{TF}_{B-L}$, and assume that it is spontaneously broken by the dynamics which generates the Majorana mass of N_R. $U(1)^{TF}_{B-L}$ is gauge anomaly free, since we have the right-handed techni-neutrino. The exchange diagrams of the $U(1)^{TF}_{B-L}$ gauge boson give an attractive force to the Dirac channel, but a repulsive force to the Majorana channel. As we will see later, the mixings between the $U(1)^{TF}_{B-L}$ and electroweak gauge bosons play a crucial role for producing the small S parameter.

Our technicolor model is based on the gauge group $SU(3)^Q_{TC} \times SU(2)^L_{TC} \times U(1)^{TF}_{B-L}$, in which the techni-fermions are transformed as,

	$SU(3)^Q_{TC}$	$SU(2)^L_{TC}$	$U(1)^{TF}_{B-L}$
$\begin{pmatrix} U_L \\ D_L \end{pmatrix}$	$\mathbf{3}$	$\mathbf{1}$	1/3
U_R, D_R	$\mathbf{3}$	$\mathbf{1}$	1/3
$\begin{pmatrix} N_L \\ E_L \end{pmatrix}$	$\mathbf{1}$	$\mathbf{3}$	–1
N_R, E_R	$\mathbf{1}$	$\mathbf{3}$	–1

Here U and D denote the techni-quarks and E denotes the techni-electron. The techni-fermions U, D, N, and E belong to the one family representation of the standard-model gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$. If one assigns the techni-quarks to the triplets of $SU(2)^L_{TC}$, the $SU(2)^L_{TC}$ becomes asymptotic non-free. In this case one needs an extra dynamical assumption that the theory has non-trivial ultraviolet fixed point.

One can ask whether the Dirac condensate $\langle \bar{N}_R N_L \rangle$ with the Majorana mass of N_R is really possible or not. We have found that such condensate really occurs by solving the Schwinger-Dyson equation in ladder and fixed coupling approximation (the detailed

[1]The Dirac condensate of the techni-electron is more favorable than the Majorana condensate by virtue of the attractive force of the electroweak interaction.

calculation will be given in ref. [9]). Since the $SU(2)^L_{TC}$ is working slowly, the fixed coupling approximation is reasonable. The critical value of the gauge coupling constant does not change much from the one in the case of vanishing Majorana mass, because relatively high energy dynamics is relevant to form the condensate in the walking technicolor model [10–13].

How strong the $U(1)^{TF}_{B-L}$ must be in order to have the Dirac condensate of the techni-neutrino? Suppose that the N_R has the Majorana mass of $M = 200 \sim 300\text{GeV}$ (the same order of the techni-fermion mass scale). We can calculate the contributions to the vacuum energy in the one gauge-boson exchange approximation when a constant Dirac or Majorana mass is formed. We can show that when

$$\frac{\alpha^{TF}_{B-L}}{m^2_{B-L}} = \frac{0.3}{(250\text{GeV})^2} = 4.8 \times 10^{-6}\ \text{GeV}^{-2}, \tag{1}$$

the Dirac condensate is favored for $M \leq 300\text{GeV}$ [9]. We take, in the present analysis, $\alpha^{TF}_{B-L} = 0.3$ and $m_{B-L} = 250\text{GeV}$, where m_{B-L} denotes the mass of the $U(1)^{TF}_{B-L}$ gauge boson X [2]. Moreover, the difference of the condensation scale between the techni-electron and the techni-neutrino can be roughly estimated from this vacuum energy calculation. We obtain the value about 60GeV, which is small in comparison with the techni-fermion mass scale $\sim 300\text{GeV}$. This result is consistent with the fact that the critical gauge coupling is not much affected by the Majorana mass in the analysis of the Schwinger-Dyson equation. We take the "constituent mass" of the techni-neutrino and the techni-electron as $m_N = 300\text{GeV}$ and $m_E = 400\text{GeV}$, respectively, in the following numerical calculation. Notice that the $\langle N_L N_L \rangle$ and $\langle N_R N_R \rangle$ condensations are disfavored, since the $U(1)^{TF}_{B-L}$ interaction acts as a repulsive force in these channels.

We should note that $U(1)_Y$ and $U(1)^{TF}_{B-L}$ is not "diagonal", namely, $\mathrm{tr}\left\{Q_Y Q^{TF}_{B-L}\right\} \neq 0$. Therefore, the bare kinetic mixing term

$$\mathcal{L}^{mix} = \omega {F_Y}^{\mu\nu} F_{X\mu\nu} \tag{2}$$

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[2] It is natural to assume that the masses m_{B-L} and M are the same order, since these masses are expected to be generated by the same dynamics.

must be introduced so that the theory is renormalizable. Although the new parameter ω may be defined in a more fundamental theory, we treat it as a free parameter in this letter. We take $\omega = 0.07$ in the following numerical calculations. This parameter plays an important role for having small S parameter [3].

Now we turn to discuss the compatibility of this model with the precision experiments. The tree-level mixing in eq.(2) yields the tree-level contributions to the S, T, and U parameters. By diagonalizing the kinetic and the mass matrices of the third component of the $SU(2)_L$, $U(1)_Y$, and $U(1)^{TF}_{B-L}$ gauge fields, we obtain the following tree-level contributions:

$$S^{\rm tree} = \frac{16}{\alpha}\frac{(c^2-r^2)s^2c^2\omega^2}{(r^2-1)^2} \simeq -0.28, \tag{3}$$

$$T^{\rm tree} = -\frac{4}{\alpha}\frac{r^2s^2\omega^2}{(r^2-1)^2} \simeq -0.10, \tag{4}$$

$$U^{\rm tree} = \frac{16}{\alpha}\frac{s^4c^2\omega^2}{(r^2-1)^2} \simeq 0.0096, \tag{5}$$

where $r = m_{B-L}/m_Z$, and c and s are the cosine and sine of the Weinberg angle, respectively. There are rather large negative contributions to the S and T parameters [5].

In addition to the oblique correction, the normalization of the neutral current and the Weinberg angle are shifted due to the mixing. The low-energy effective four-fermion interactions generated by both the Z and the $U(1)^{TF}_{B-L}$ gauge boson exchanges are (following the notation of ref. [14])

$$\mathcal{L}^{neuteral}_{eff} = \frac{1}{m_Z^2} J^f_\mu J^{f'\mu}, \tag{6}$$

$$J^f_\mu = \frac{e_*}{c_* s_*}\sqrt{Z_*}\bar{f}\gamma_\mu \left(I_3 - s_*^2 Q\right) f, \tag{7}$$

where f and f' are the ordinary quarks and leptons. The shifts from the standard model, $\delta Z_* = Z_* - Z_*|_{SM}$ and $\delta s_*^2 = s_*^2 - s_*^2|_{SM}$, are given by [5]

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[3]A similar mixing between the additional $U(1)$ and the electroweak gauge bosons has been also considered by Holdom [5].

$$\delta Z_* = \frac{4r^2 s^2 \omega^2}{(r^2-1)^2} \simeq 7.9 \times 10^{-4}, \tag{8}$$

$$\delta s_*^2 = \frac{4s^2 c^2 \omega^2}{r^2-1} \simeq 5.3 \times 10^{-4}. \tag{9}$$

These shifts are detectable in principle by comparing the data at Z-pole, where the Z boson exchange dominates, with the data of low energy neutral current experiments, ν_μ-q scattering, ν_μ-e scattering, and so on. But these shifts are too small to be detectable in the present low energy experiments.

Next we calculate the 1-loop techni-fermion contributions to the vacuum polarizations of the electroweak gauge bosons, and estimate the contribution to the S, T, and U parameters. The mass of the techni-fermion is treated as a constant ("constituent mass"). Since we assume no custodial symmetry breaking in the techni-quark sector, the contributions from the techni-quark sector to the three parameters are

$$S^Q = \frac{N_{TC}}{6\pi} \times 3 \simeq 0.48, \tag{10}$$

$$T^Q = 0, \tag{11}$$

$$U^Q = 0, \tag{12}$$

where $N_{TC} = 3$. There is a large positive contribution to the S parameter as usual in one-family technicolor model.

The contribution from the techni-lepton sector is a little complicated, because of the Majorana mass of the right-handed techni-neutrino. The formulae of the techni-lepton contributions to the S, T, and U parameters have already been given in ref. [6]:

$$\begin{aligned} S^L = \frac{N_{TC}}{6\pi}\Bigg[&\frac{3}{2} + c_M^2 \ln\frac{m_1^2}{m_E^2} + s_M^2 \ln\frac{m_2^2}{m_E^2} \\ &-s_M^2 c_M^2 \left(\frac{8}{3} + f_1(m_1,m_2) - f_2(m_1,m_2)\ln\frac{m_1^2}{m_2^2}\right)\Bigg], \end{aligned} \tag{13}$$

$$\begin{aligned} T^L = \frac{N_{TC}}{16\pi s^2 c^2 m_Z^2}\Bigg[&c_M^2\left(m_1^2 + m_E^2 - \frac{2m_1^2 m_E^2}{m_1^2 - m_E^2}\ln\frac{m_1^2}{m_E^2}\right) \\ &+s_M^2\left(m_2^2 + m_E^2 - \frac{2m_2^2 m_E^2}{m_2^2 - m_E^2}\ln\frac{m_2^2}{m_E^2}\right) \end{aligned}$$

$$
-s_M^2 c_M^2 \left(m_1^2 + m_2^2 - 4m_1 m_2 + 2\frac{m_1^3 m_2 - m_1^2 m_2^2 + m_1 m_2^3}{m_1^2 - m_2^2} \ln \frac{m_1^2}{m_2^2} \right) \Bigg], \tag{14}
$$

$$
\begin{aligned}
U^L = \frac{N_{TC}}{6\pi} \Bigg[& c_M^2 \left(f_3(m_1, m_E) \ln \frac{m_1^2}{m_E^2} + \frac{4m_1^2 m_E^2}{(m_1^2 - m_E^2)^2} \right) \\
& + s_M^2 \left(f_3(m_2, m_E) \ln \frac{m_2^2}{m_E^2} + \frac{4m_2^2 m_E^2}{(m_2^2 - m_E^2)^2} \right) \\
& - \frac{13}{6} + s_M^2 c_M^2 \left(\frac{8}{3} + f_1(m_1, m_2) - f_2(m_1, m_2) \ln \frac{m_1^2}{m_2^2} \right) \Bigg],
\end{aligned} \tag{15}
$$

where

$$
f_1(m_1, m_2) = \frac{3m_1 m_2^3 + 3m_1^3 m_2 - 4m_1^2 m_2^2}{(m_1^2 - m_2^2)^2}, \tag{16}
$$

$$
f_2(m_1, m_2) = \frac{m_1^6 - 3m_1^4 m_2^2 + 6m_1^3 m_2^3 - 3m_1^2 m_2^4 + m_2^6}{(m_1^2 - m_2^2)^3}, \tag{17}
$$

$$
f_3(m_1, m_2) = \frac{m_1^6 - 3m_1^4 m_2^2 - 3m_1^2 m_2^4 + m_2^6}{(m_1^2 - m_2^2)^3}, \tag{18}
$$

$$
m_1 = \frac{\sqrt{M^2 + 4m_N^2} - M}{2}, \quad m_2 = m_1 + M, \tag{19}
$$

$s_M = -\sqrt{m_1/(m_1 + m_2)}$, and $c_M = \sqrt{m_2/(m_1 + m_2)}$. Since the Majorana mass breaks the custodial symmetry, we expect a large contribution to the T parameter. The mass difference between the techni-neutrino and the techni-electron due to the Majorana mass gives positive contribution to the T parameter, but the effect of the Majorana mass itself gives the negative contribution to the T parameter. The negative contribution becomes quite substantial when the magnitude of the Majorana mass is comparable with the techni-lepton masses.

In total, the contribution to the T parameter is $0 < T^L < 0.3$ for $M = 200 \sim 300$GeV with $m_N = 300$GeV and $m_E = 400$GeV. The smaller splitting between m_N and m_E results in smaller value of T^L. The behavior of the contribution to the U parameter is similar to the T parameter, but the magnitude is smaller. Although the Majorana mass gives the negative contribution to the S parameter, the magnitude is very small, when the Majorana mass is comparable with the techni-lepton masses. The mass splitting between the techni-neutrino and techni-electron also gives the negative contribution to the S parameter [7], but the magnitude is small. We should stress here that the Majorana mass of the right-handed

techni-neutrino itself does not give an important contribution to have the small S parameter. Thus, our model is completely different from the model proposed in ref [6].

The mixings between the massive $U(1)^{TF}_{B-L}$ and the neutral electroweak gauge bosons are generated also by the quantum effects. The exchanges of the $U(1)^{TF}_{B-L}$ gauge boson through the mixings (see fig.1) contribute to the vacuum polarizations $\Pi'_{3Y}(0)$, $\Pi_{33}(0)$, and $\Pi'_{33}(0)$, and change the values of the S, T, and U parameters, where the vacuum polarizations are expanded as

$$\Pi^{\mu\nu}(q) = \Pi(q^2)g^{\mu\nu} + (q^\mu q^\nu \text{ term}), \tag{20}$$

$$\Pi(q^2) = \Pi(0) + q^2\Pi'(0) + \cdots. \tag{21}$$

The mixings between $U(1)^{TF}_{B-L}$ gauge boson and W^3 which are obtained from the 1-loop diagram of the techni-leptons (fig.2) are

$$\begin{aligned}\Pi_{3X}(0) = -\frac{N_{TC}}{8\pi^2}\Bigg[& c_M^2(c_M^2 - s_M^2)m_1^2\left(\ln\frac{\Lambda^2}{m_1^2} - 1\right) + s_M^2(s_M^2 - c_M^2)m_2^2\left(\ln\frac{\Lambda^2}{m_2^2} - 1\right) \\ & -s_M^2 c_M^2\left\{\frac{m_1^3(m_1 - 2m_2)}{m_2^2 - m_1^2}\ln\frac{\Lambda^2}{m_1^2} - \frac{m_2^3(m_2 - 2m_1)}{m_2^2 - m_1^2}\ln\frac{\Lambda^2}{m_2^2} + \frac{1}{2}(m_1^2 + m_2^2)\right\}\Bigg],\end{aligned} \tag{22}$$

$$\begin{aligned}\Pi'_{3X}(0) = \frac{N_{TC}}{16\pi^2}\Bigg[& -\frac{1}{3} - \frac{1}{3}c_M^2(c_M^2 - s_M^2)\ln\frac{m_1^2}{m_E^2} - \frac{1}{3}s_M^2(s_M^2 - c_M^2)\ln\frac{m_2^2}{m_E^2} \\ & +2c_M^2 s_M^2\left\{\frac{8}{9} + \frac{m_1 m_2}{(m_2^2 - m_1^2)^2}\left(m_1^2 + m_2^2 - \frac{4}{3}m_1 m_2\right) - \frac{2}{3}\ln\frac{m_1 m_2}{m_E^2}\right. \\ & \left. -\frac{1}{3}\frac{m_1^6 - 3m_1^4 m_2^2 + 6m_1^3 m_2^3 - 3m_1^2 m_2^4 + m_2^6}{(m_2^2 - m_1^2)^3}\ln\frac{m_2^2}{m_1^2}\right\}\Bigg].\end{aligned} \tag{23}$$

We introduce the ultraviolet cut off $\Lambda = 1$TeV (scale of the technicolor dynamics) in the calculation of the mass mixing $\Pi_{3X}(0)$. By introducing this physical cut off, we approximately include the effect of the dumping of the techni-lepton mass function at the scale Λ.

The mixings between the $U(1)^{TF}_{B-L}$ and the $U(1)_Y$ gauge bosons are also obtained in the same way as above, and given by the followings relations;

$$\Pi_{YX}(0) = -\Pi_{3X}(0), \tag{24}$$

$$\Pi'_{YX}(0) = -\Pi'_{3X}(0) + 2\omega. \tag{25}$$

Note that the kinetic mixing $\Pi'_{YX}(0)$ contains a constant 2ω which comes from the ω-term in eq.(2). The ultraviolet divergence of $\Pi'_{YX}(0)$ is absorbed by the renormalization of ω. The simple relations in eqs.(24) and (25) are understood by considering the fact that $(Y/2)_N = -(I_3)_N$, the techni-electron Dirac mass does not break $U(1)^{TF}_{B-L}$ symmetry, and $(Y/2)_E = -(I_3)_E + (B-L)_E$.

The correction to the vacuum polarization $\Pi^{\mu\nu}_{33}$ ($\Pi_{33}(0)$ and $\Pi'_{33}(0)$) due to the s-channel $U(1)^{TF}_{B-L}$ gauge boson exchange is given by

$$\Pi_{33}(0) = \Pi_{3X}(0)\frac{4\pi\alpha_{B-L}}{-m^2_{B-L}}\Pi_{3X}(0), \tag{26}$$

$$\begin{aligned}\Pi'_{33}(0) = &\Pi'_{3X}(0)\frac{4\pi\alpha_{B-L}}{-m^2_{B-L}}\Pi_{3X}(0)\\ &+ \Pi_{3X}(0)\frac{4\pi\alpha_{B-L}}{-m^2_{B-L}}\Pi'_{3X}(0)\\ &+ \Pi_{3X}(0)\frac{4\pi\alpha_{B-L}}{-m^4_{B-L}}\Pi_{3X}(0).\end{aligned} \tag{27}$$

These give the positive contributions to the T and U parameters:

$$T^{B-L} = \frac{4\pi}{s^2c^2m_Z^2}\left[\Pi_{11}(0) - \Pi_{33}(0)\right], \tag{28}$$

$$U^{B-L} = 16\pi\left[\Pi'_{11}(0) - \Pi'_{33}(0)\right], \tag{29}$$

where $\Pi_{11}(0)$ and $\Pi'_{11}(0)$ are zero in the present approximation. The T parameter increases quickly as the Majorana mass becomes larger. (This is the 2-loop level contribution, since $\Pi_{3X}(0)$ is estimated at the 1-loop level.) When $m_N = 300$GeV and $m_E = 400$GeV, $T^{B-L} < 0.35$ for $M < 300$GeV. The behavior of the contribution to the U parameter is similar to the T parameter, but the magnitude is smaller.

The correction to the vacuum polarization $\Pi'_{3Y}(0)$ due to the s-channel $U(1)^{TF}_{B-L}$ gauge boson exchange is given by

$$\begin{aligned}\Pi'_{3Y}(0) = &\Pi'_{3X}(0)\frac{4\pi\alpha_{B-L}}{-m^2_{B-L}}\Pi_{YX}(0)\\ &+ \Pi_{3X}(0)\frac{4\pi\alpha_{B-L}}{-m^2_{B-L}}\Pi'_{YX}(0)\\ &+ \Pi_{3X}(0)\frac{4\pi\alpha_{B-L}}{-m^4_{B-L}}\Pi_{YX}(0).\end{aligned} \tag{30}$$

Note that the second term contains the 1-loop contribution, since $\Pi'_{YX}(0)$ contains the tree-level constant term. Therefore, we have a large contribution to the S parameter:

$$S^{B-L} = -16\pi\Pi'_{3Y}(0). \tag{31}$$

This contribution is negative taking ω positive, and the magnitude is large enough to cancel the large positive contribution from the techni-quark sector, together with the tree-level contribution in eq.(3). We should stress here that this large negative contribution disappears when the Majorana mass vanishes, since $\Pi_{3X}(0)$ vanishes if $M = 0$. Therefore, both the Majorana mass and the ω-term in eq.(2) are needed in order to have the large negative contribution. Holdom has already found that the ω-term gives rather large negative contribution to the S parameter at tree level. But the tree-level contribution is not large enough to cancel out the large positive value in the QCD-like one-family technicolor model, while keeping the shifts of eqs.(8) and (9) small [5].

The Majorana mass dependences of the total values of the S, T, and U parameters are shown in fig.3, fig.4, and fig.5, respectively. All three parameters are consistent with the experimental constraints, when the Majorana mass of the right-handed techni-neutrino $M < 300$GeV. Remember that we take the parameters α_{B-L} and m_{B-L} so that the correct electroweak symmetry breaking really occurs with $M < 300$GeV. And the mass splitting between the techni-neutrino and techni-electron (100GeV) is a natural one which comes from the estimation of the vacuum energy. We set the value of ω to 0.07 so that all the things become consistent. Although the value of the S parameter may be enhanced by the factor two or more due to non-perturbative effects, this model will be still consistent by virtue of the large cancelation of the S parameter in the region $M \simeq 200$GeV.

We should note that the T parameter is very sensitive to the mass deference between the techni-neutrino and techni-electron. If we take smaller mass difference, the T parameter becomes negative in the region $M < 300$GeV. If we take the values $m_N = 340$GeV and $m_E = 400$GeV, for instance, the minimum value of T is about -0.2 at $M \simeq 250$GeV, while the S and U parameters are still consistent with the experimental constraints. Therefore,

we may explain the deviation of $R_b = \Gamma_b/\Gamma_{had}$ from the standard-model value by considering the effect of the diagonal extended technicolor (ETC) gauge boson [15,16], since the large positive contribution to the T parameter [17] due to the diagonal ETC boson can be cancelled out.

The number of pseudo-Nambu-Goldstone bosons is reduced in comparison with the naive one-family technicolor theory, since the approximate chiral symmetry is largely reduced by the separate structure of the technicolor gauge group. If the standard-model gauge interaction is switched off, the non-anomalous chiral symmetry of the techni-fermion sector is $SU(6)^Q_L \times SU(6)^Q_R \times SU(2)^L_L \times U(1)^Q_V \times U(1)^L_Y$. Techni-fermion condensates break this chiral symmetry to $SU(6)^Q_V \times U(1)^Q_V \times U(1)^L_{em}$, and the currents corresponding to the broken symmetries are

$$J^{ai}_\mu = \bar{Q}\gamma_\mu\gamma_5\frac{\lambda^a}{2}\frac{\tau^i}{2}Q = F_Q\partial_\mu\Theta^{ai} + \cdots, \tag{32}$$

$$J^{a}_\mu = \bar{Q}\gamma_\mu\gamma_5\frac{\lambda^a}{2}Q = F_Q\partial_\mu\Theta^{a} + \cdots, \tag{33}$$

$$J^{Qi}_\mu = \bar{Q}\gamma_\mu\gamma_5\frac{\tau^i}{2}Q = F_Q\partial_\mu\Phi^i_Q + \cdots, \tag{34}$$

$$J^{Li}_\mu = \bar{L}\gamma_\mu\frac{1-\gamma_5}{2}\frac{\tau^i}{2}L = F_L\partial_\mu\Phi^i_L + \cdots, \tag{35}$$

where $Q = (U\ D)^T$ and $L = (N\ E)^T$, and the last equalities in each equations denote the effective couplings of the Nambu-Goldstone bosons with decay constants F_Q and F_L. The scales of F_Q and F_L are determined by the dynamics of $SU(3)^Q_{TC}$ and $SU(2)^L_{TC}$, respectively. The true Nambu-Goldstone bosons which couple with the electroweak currents are

$$\Pi^i = \Phi^i_L\cos\varphi - \Phi^i_Q\sin\varphi, \tag{36}$$

and the pseudo-Nambu-Goldstone bosons are Θ^{ai}, Θ^a, and

$$P^i = \Phi^i_L\sin\varphi + \Phi^i_Q\cos\varphi, \tag{37}$$

where $\tan\varphi = F_Q/F_L$, and the decay constant of the true Nambu-Goldstone bosons is $\sqrt{F_Q^2+F_L^2}$. The masses of the colored pseudo-Nambu-Goldstone bosons, Θ^{ai} and Θ^a, are

expected to be about 300GeV. The electroweak interaction gives the mass to P^i. Although the naive estimation for the mass of P^i is about 10GeV, it will be lifted up by the walking technicolor dynamics of $SU(2)^L_{TC}$.

Finally, we comment on a possible physics beyond the present model. Because of the strong coupling of $U(1)^{TF}_{B-L}$ gauge interaction ($\alpha_{B-L} = 0.3$ at the electroweak symmetry breaking scale) and the presence of many $U(1)^{TF}_{B-L}$ charged techni-fermions, the gauge coupling constant for $U(1)^{TF}_{B-L}$ blows up at about 3TeV. Therefore, we must invoke some new physics in the TeV region. The technicolor structure may be changed there like in the extended technicolor theory embedding the $U(1)^{TF}_{B-L}$ in some non-Abelian gauge group.

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FIGURES

FIG. 1. The diagrams which contribute to the vacuum polarizations $\Pi'_{3Y}(0)$, $\Pi_{33}(0)$, and $\Pi'_{33}(0)$. We consider only the diagrams in which the $U(1)^{TF}_{B-L}$ gauge boson X is exchanged in s-channel.

FIG. 2. The diagram which gives the mixing between the $U(1)^{TF}_{B-L}$ gauge boson X and W^3. Only the techni-leptons contribute to the loops, since only the Majorana mass of the right-handed techni-neutrino breaks $U(1)^{TF}_{B-L}$ gauge symmetry.

FIG. 3. The Majorana mass dependence of the S parameter. The region between the two horizontal lines is allowed by the experiments [2]. The reference point is taken as $m_t = 175$GeV and $m_H = 1$TeV.

FIG. 4. The Majorana mass dependence of the T parameter. The region between the two horizontal lines is allowed by the experiments [2]. The reference point is taken as $m_t = 175$GeV and $m_H = 1$TeV.

FIG. 5. The Majorana mass dependence of the U parameter. The region between the two horizontal lines is allowed by the experiments [2]. The reference point is taken as $m_t = 175$GeV and $m_H = 1$TeV.

Fig.3

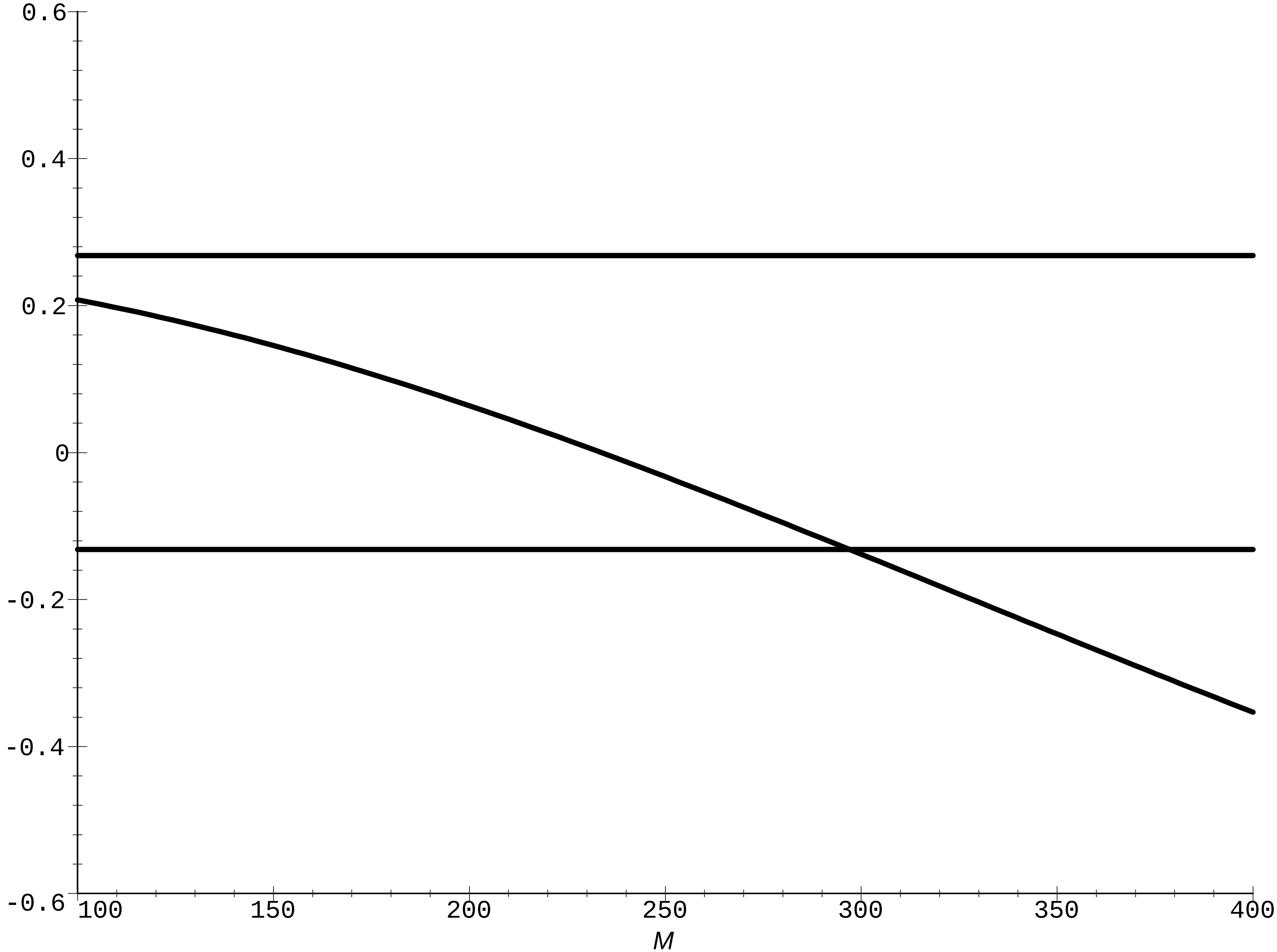


Fig.4

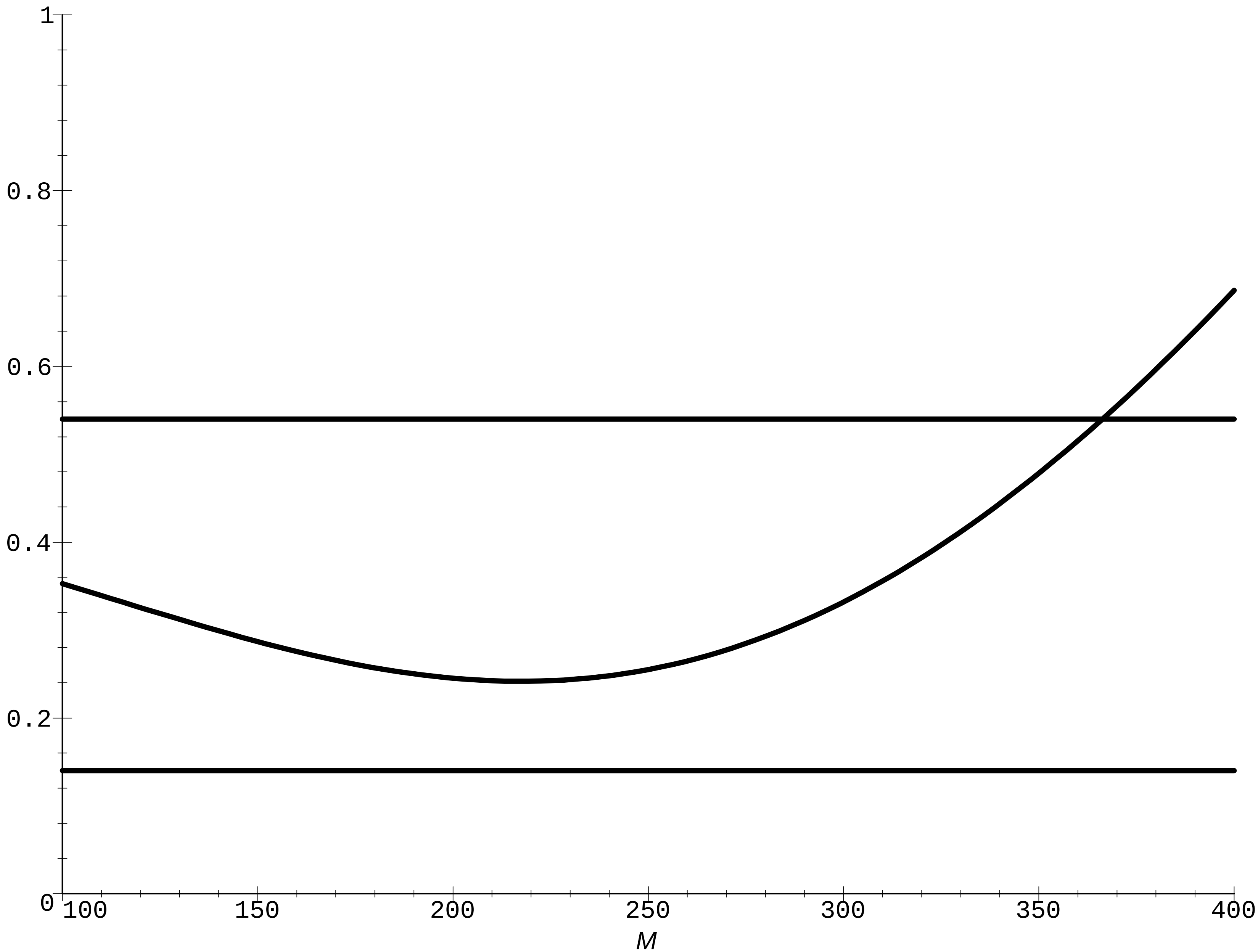
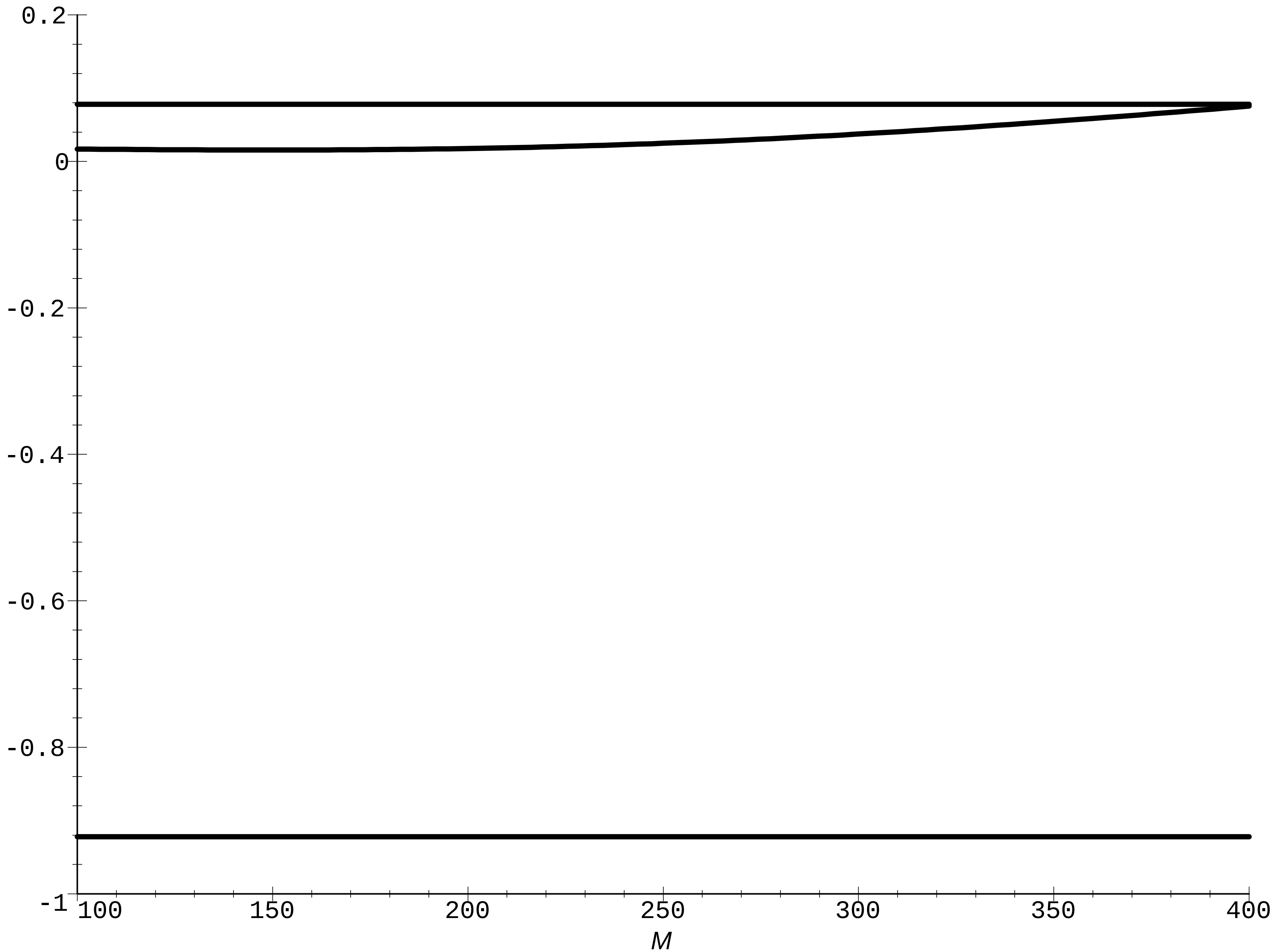


Fig.5



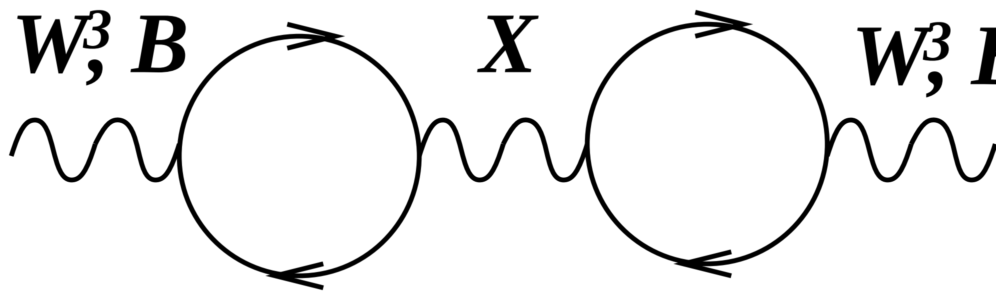


Fig.1

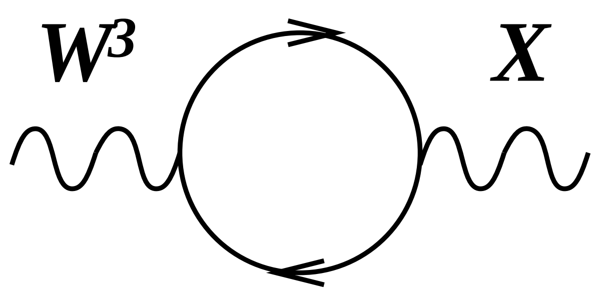


Fig.2